Operative Techniques in
Thoracic and
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The Norwood Operation With Innominate Artery and Descending Aortic Cannulation, Performed With Continuous Mildly Hypothermic Bypass

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Conventional perfusion technique for the Norwood operation relies on deep hypothermia for protection of the body during construction of the neoaortic arch, with or without the provision of cold antegrade perfusion into the cerebral circulation. Bypass time required for cooling and warming, the exposure of the lower body to prolonged ischemia, and the effects of hypothermia itself, may contribute to postoperative oliguria and third-space fluid gain, and may prolong recovery. In this article, a technique is presented for exposure and cannulation of the descending aorta. This, combined with direct cannulation of the innominate artery, allows continuation of full-flow bypass to the entire body throughout repair, and obviates the use of deep hypothermia. Modifications of the conduct of operation are presented which take advantage of the absence of cardiopulmonary bypass time spent cooling and warming to reduce the overall duration of bypass and myocardial ischemia.
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KEYWORDS **Norwood operation, perfusion technique, descending aorta cannulation, acute kidney injury, deep hypothermic circulatory arrest**

Introduction

Survival after the Norwood operation has improved considerably in the 3 decades since its wide application, with multiple single centers reporting discharge survival greater than 90%.[1-3] However, morbidity continues to be high, with postoperative oliguria, delayed sternal closure, postoperative mechanical ventilation, and requirement for parenteral nutrition occurring frequently. Some portion of the morbidity is due to the single ventricle physiology, which persists after surgery, with its inherent physiological limitations. However, a perioperative factor common to this and other neonatal operations associated with high morbidity is the continued use of deep hypothermia and circulatory arrest or selective cerebral perfusion.

Deep hypothermia and periods of stopped or limited perfusion were once in common use for all neonatal cardiac surgery; however, with refinement of perfusion equipment and operative techniques, deep hypothermia and circulatory arrest have now mostly fallen from use for operations not involving reconstruction of the aortic arch. In an effort to reduce the morbidity and mortality associated with the Norwood operation and other operations that do require reconstruction of the aortic arch, Imoto et al[4,5] described cannulation of both the innominate artery and the descending aorta above the diaphragm to allow continuous flow to the entire body during reconstruction of the aortic arch. This technique has failed to become popular, perhaps owing to the perceived difficulty of incorporating the descending cannulation into an already-complex operation.

The technique described later incorporates a simplified exposure of the descending aorta, which is cannulated and connected to a branched arterial line. Because cooling is not required before aortic reconstruction can begin, the majority of dissection and mobilization precede the initiation of bypass. The heart is allowed to beat throughout all except the proximal aortic reconstruction. An additional modification, to the shaping of the aortic patch, is presented, which facilitates use of material other than pulmonary homograft.

Dual arterial cannulation is applicable to all operations requiring reconstruction of the aortic arch such as interrupted or hypoplastic arch and has led to the complete avoidance of deep hypothermia or circulatory arrest at the author's institution. The Norwood technique described here takes advantage of the dual cannulation to avoid hypothermia, avoid interruption of perfusion to any part of the body, and reduce the times of extracorporeal circulation and myocardial ischemia, while safely and expeditiously achieving a hemodynamically optimum result (Figs. 1-10).

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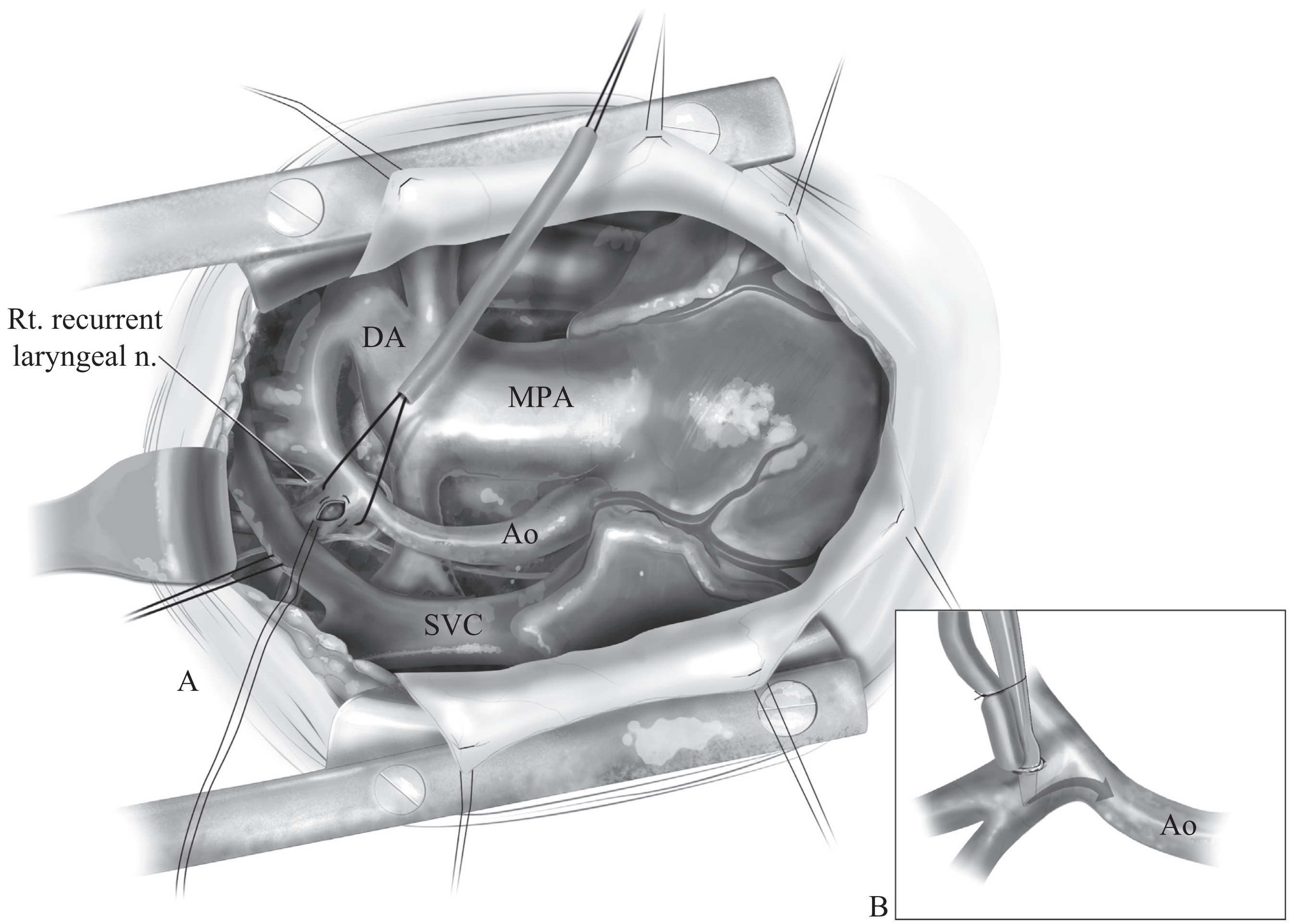

Figure 1 (A) Setup for the operation includes placement of 2 arterial monitoring lines, 1 in the right upper extremity and 1 in the lower body (umbilical, tibial, or femoral). The Sano conduit should be prepared before incision (Fig. 6A). A piece of ePTFE is cut from one end of the selected tube, cut longitudinally, and flattened. An end of the tube is sutured to a circular hole cut in the patch using running prolene suture, and the patch-to-tube suture line is sealed with cyanoacrylate adhesive (Dermabond, Ethicon). The dual cannulation and operation are performed through a standard sternotomy incision; no superior or inferior extension is required. Because no time is required for cooling before starting the arch reconstruction, all dissection should be completed before initiating bypass. For safety, heparin is administered and the innominate artery cannula is inserted before dissection around the ductus and distal arch. A retractor clamped to the crossmember of the sternal retractor facilitates the innominate artery exposure, as does a retraction suture placed on the innominate vein where it crosses the innominate artery, and secured inside the skin of the upper incision. Traction can be applied to a snare placed loosely around the origin of the innominate artery, being careful not to pull hard enough to compress the junction of the proximal transverse arch with the distal ascending aorta, obstructing coronary flow. Note that the right recurrent laryngeal nerve passes beneath the right subclavian artery just distal to the innominate bifurcation. The innominate artery is cannulated directly through a longitudinal purse string in the distal innominate artery. (B) Direction of the bevel of the arterial cannula toward the aorta and the coronary circulation ensures that the ascending aortic and coronary pressure will be at least as great as the measured pressure at the right wrist. PTFE = polytetrafluoroethylene.

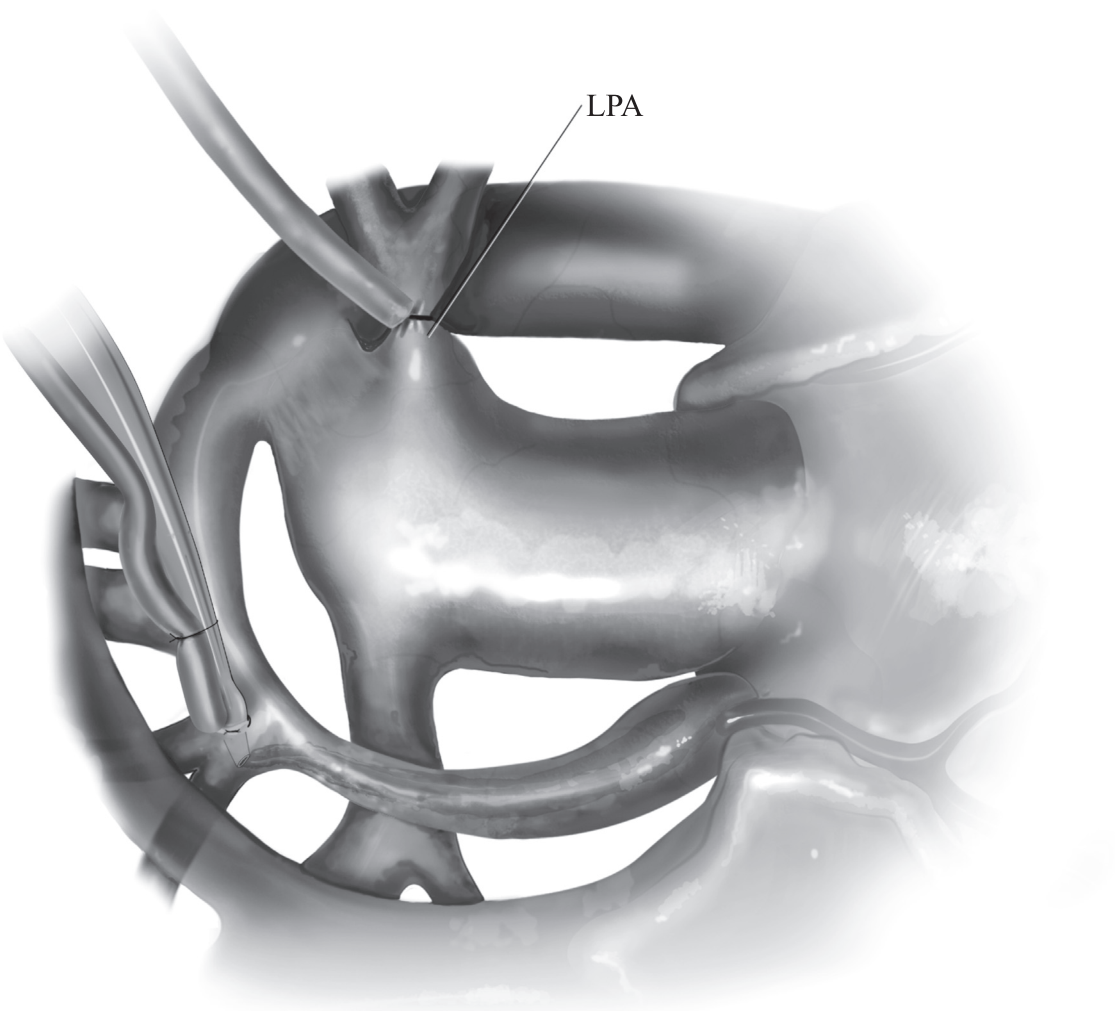

Figure 2 Before dissection in the left hilum, and before entry of the left pleural space to expose the descending aorta, the left pulmonary artery is snared shut. Although in conventional technique the pulmonary artery is depressurized after commencing bypass and cooling, the high flow and pressure to which the pulmonary vasculature is exposed during prebypass dissection, in the author's earlier experience, sometimes lead to troublesome pulmonary parenchymal and airway hemorrhage. This has not been a problem since the early snare occlusion of the left pulmonary artery was adopted. We will close the left pulmonary artery even in cases such as isolated hypoplastic arch with closed ductus, where there is not increased pulmonary flow but there is elevated pulmonary pressure.

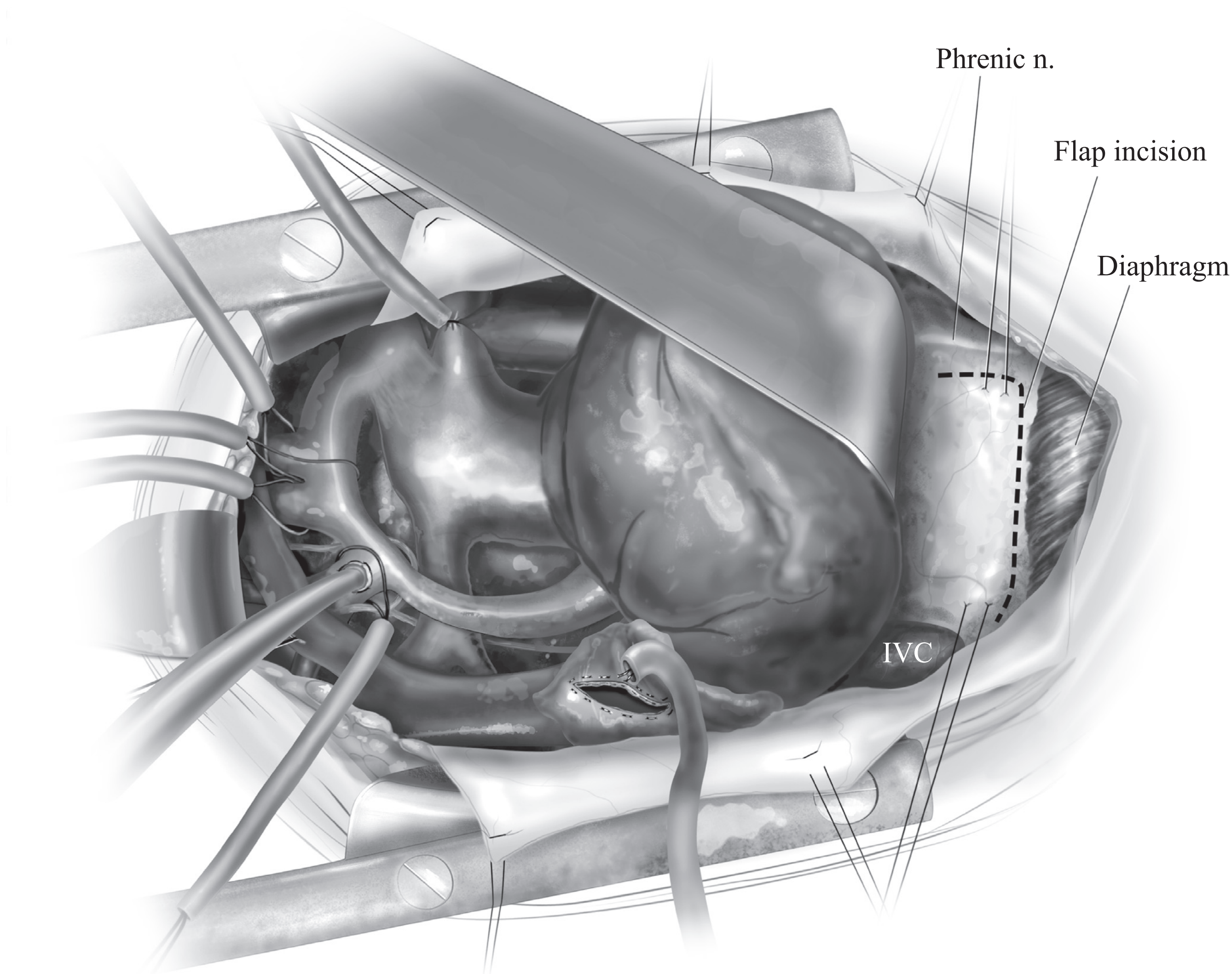

Figure 3 Silk no. 3 snares are placed loosely around the innominate artery, the left carotid and subclavian arteries, and the proximal transverse arch. Dissection around the ductal insertion is deferred until after descending cannulation. The venous cannulation site can be prepared in case of emergency during the descending exposure. Caval venous cannulae are not inserted yet, as they can interfere with venous return during lifting of the heart. For the Norwood operation without intracardiac work, the atrial purse string is made 2 cm long, so that later the septectomy can be performed through the cannulation incision during a brief period of pump sucker-return bypass. Setup for the descending cannulation is shown in this figure. The cardiac apex is lifted (not compressed) with a malleable retractor. A pericardial stay is placed in the left pericardio-phrenic reflection. The phrenic nerve is visualized through the pericardium. An incision is made through the pericardium into the left pleural space, beginning 1 cm to the right of the nerve, continuing rightward along the reflection of the posterior pericardium onto the diaphragm, stopping at the left aspect of the inferior vena cava. The left end of the incision is then continued cephalad, parallel to the phrenic nerve, for a distance of 1-1.5 cm. Retraction stitches are placed at the right and left ends of the created pericardial flap.

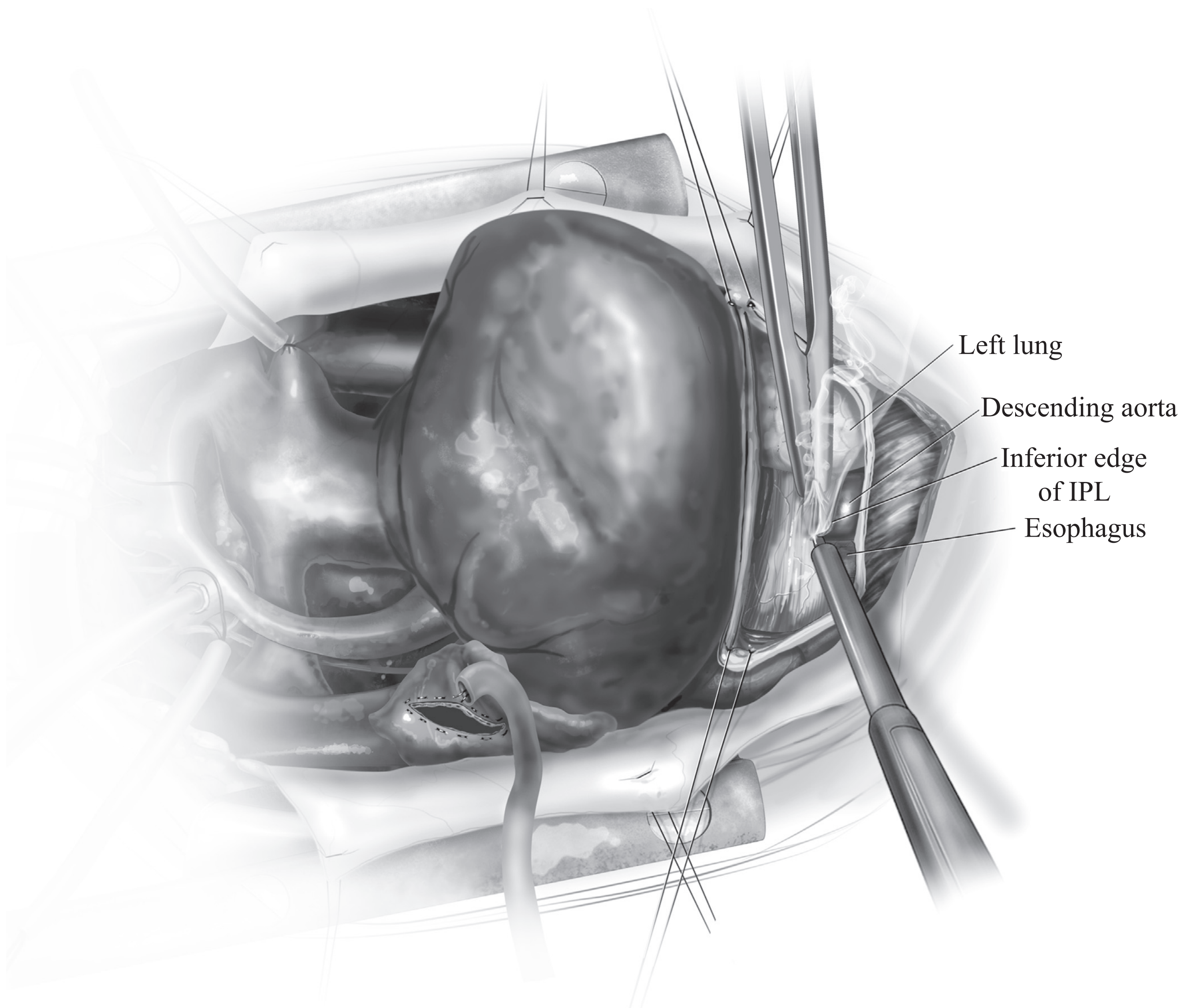

Figure 4 With retraction on the pericardial stays, the heart is elevated with the apex out of the incision. This has uniformly been tolerated with good hemodynamics, as long as the heart is lifted and not compressed. The inferior edge of the inferior pulmonary ligament is grasped and incised superiorly. Great care is taken so that the parenchyma of the lung is not grasped or roughly retracted, to avoid starting hemorrhage. After the inferior pulmonary ligament has been divided to the inferior pulmonary vein, the aorta will be plainly visible. The esophagus overlaps the right anterior aspect of the aorta.

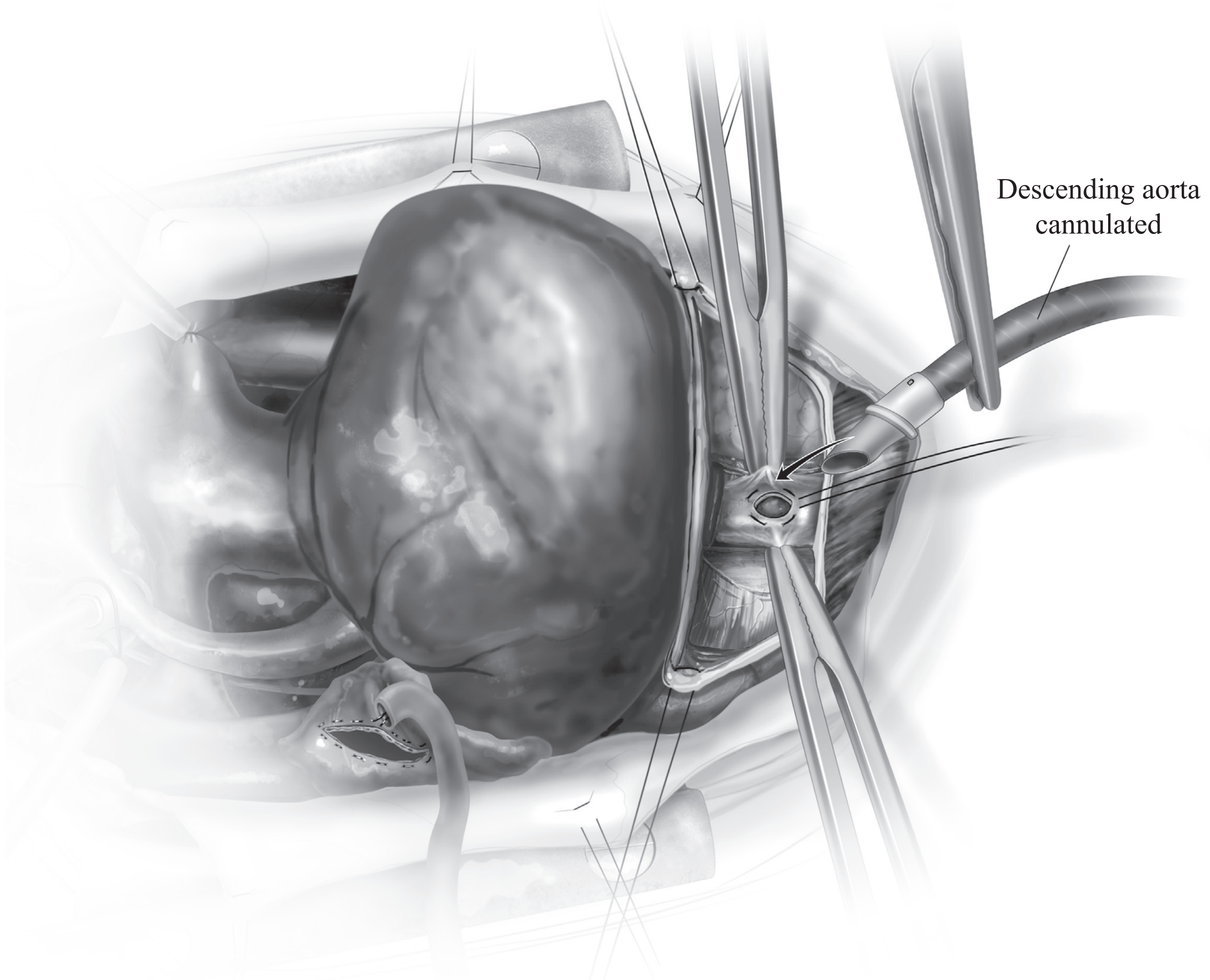

Figure 5 The anterior aspect of the aorta is dissected, and the vessel is cannulated as routine. In the author's early experience, the aorta was circumferentially dissected, and a heavy silk was passed around the aorta, to aid in control if clamping might be required, but this is no longer felt necessary. To achieve balanced flow to the upper and lower body, identical cannulae are used for the innominate and the descending aorta. An ideal cannula for this technique is the 8 French RMI (Edwards, PEDA-008-SB), 2 of which are adequate for a patient weighing up to 6 kg. The 2 arterial cannulae will be attached to a branched arterial line. It is important that, after inserting and connecting the inferior cannula, the line to the innominate cannula is temporarily clamped so that the usual sequence of checking for equal mean pressures and for satisfactory infusion inflow can be performed for the descending cannula.

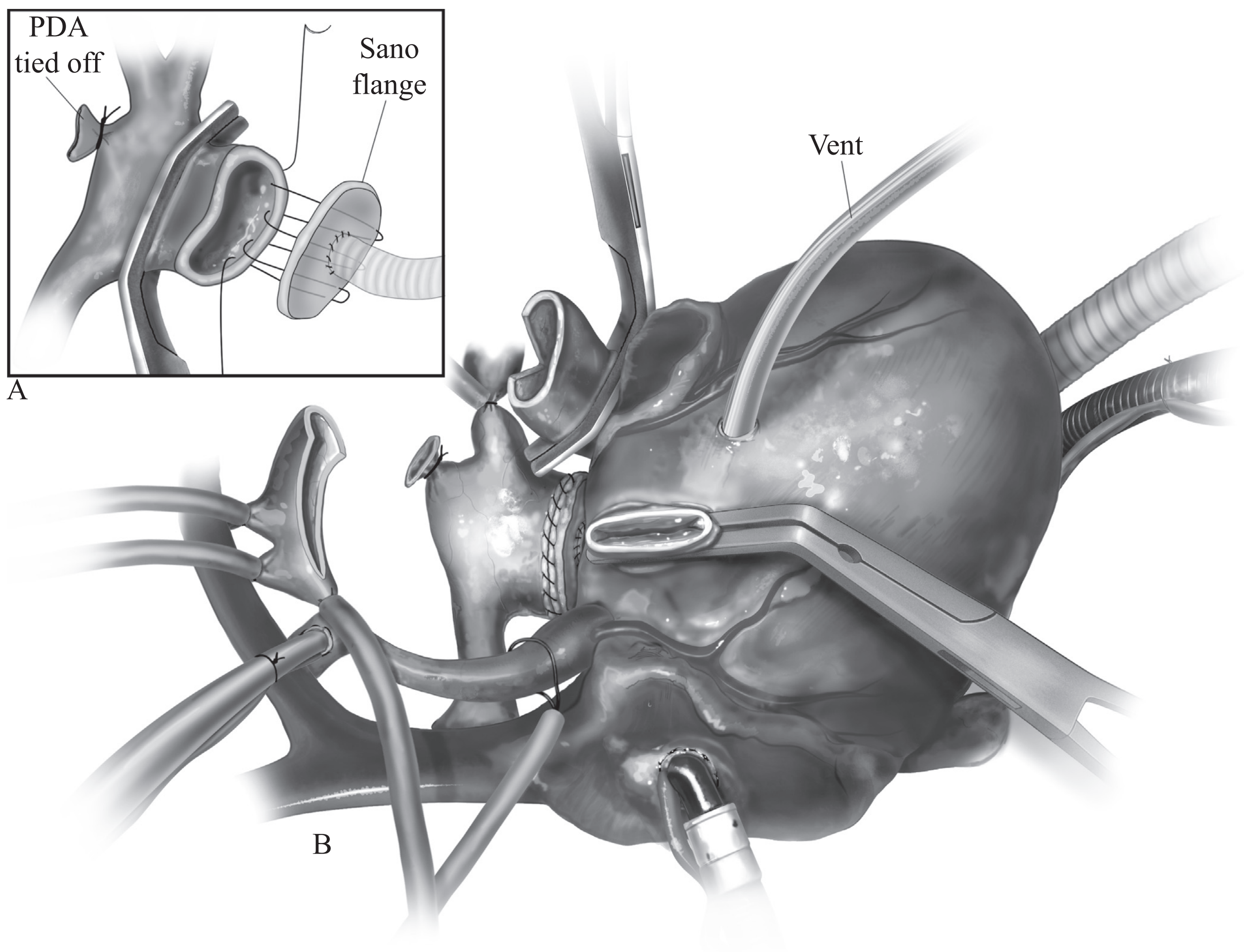

Figure 6 The atrial cannula is inserted. The dissection of the transverse arch, the ductal insertion, and the descending aorta may now be completed in relative safety because if there is any injury to the ductus or its insertion, bypass can be initiated and clamps and snares applied proximal and distal to the site of bleeding. The final step before initiation of bypass is to place loosely a circumferential suture ligature around the ductus proximally and distally. Cardiopulmonary bypass is now started. Temperature for a routine Norwood operation is typically selected at 34°-36°, but if there is extensive intracardiac work to be done during myocardial ischemic time, a lower temperature such as 32° might be selected. The ductus ligatures are tied down and the ductus is divided. The pulmonary bifurcation is completely mobilized. The main pulmonary artery is transected just before the branches. A clamp is applied across the branches, and the flanged end of the previously prepared Sano shunt is cut in a circular shape and sutured onto the distal main pulmonary artery (see inset). The Sano is then pulled behind the heart, putting it out of the way of the aortic reconstruction until later in the operation. Looking through the pulmonary valve, a site is selected for the Sano ventriculotomy and is punctured from inside with a right-angle clamp. A 10-F vent can be placed through this puncture site, and a clamp applied to the pulmonary root, to prevent blood ejected from the beating heart from interfering with vision of the aorta. At this point, if there is aortic atresia, the atrial septum can be excised with the heart beating. The atrial cannula is removed, 2 pump suckers are used to return blood to the pump, the atrial cannulation incision is retracted, and the flap of fossa ovalis is excised. If there is mitral and aortic stenosis, such that there might be aortic ejection of air, the septectomy can be performed later, during the myocardial ischemic time. The snares are tightened at the proximal transverse aortic arch, the left carotid, and the left subclavian, and a clamp is applied to the descending aorta, at least 1 cm distal to the end of the ductal insertion, being careful not to include the left recurrent laryngeal nerve in the clamp. The aorta is transected proximal and distal to the ductal insertion point, and all the thick, spongy-appearing ductal tissue is excised. The inferior aspect of the transverse aortic arch is incised longitudinally as far proximal as possible. The posterior aspect of the descending aorta is incised longitudinally for 5 mm.

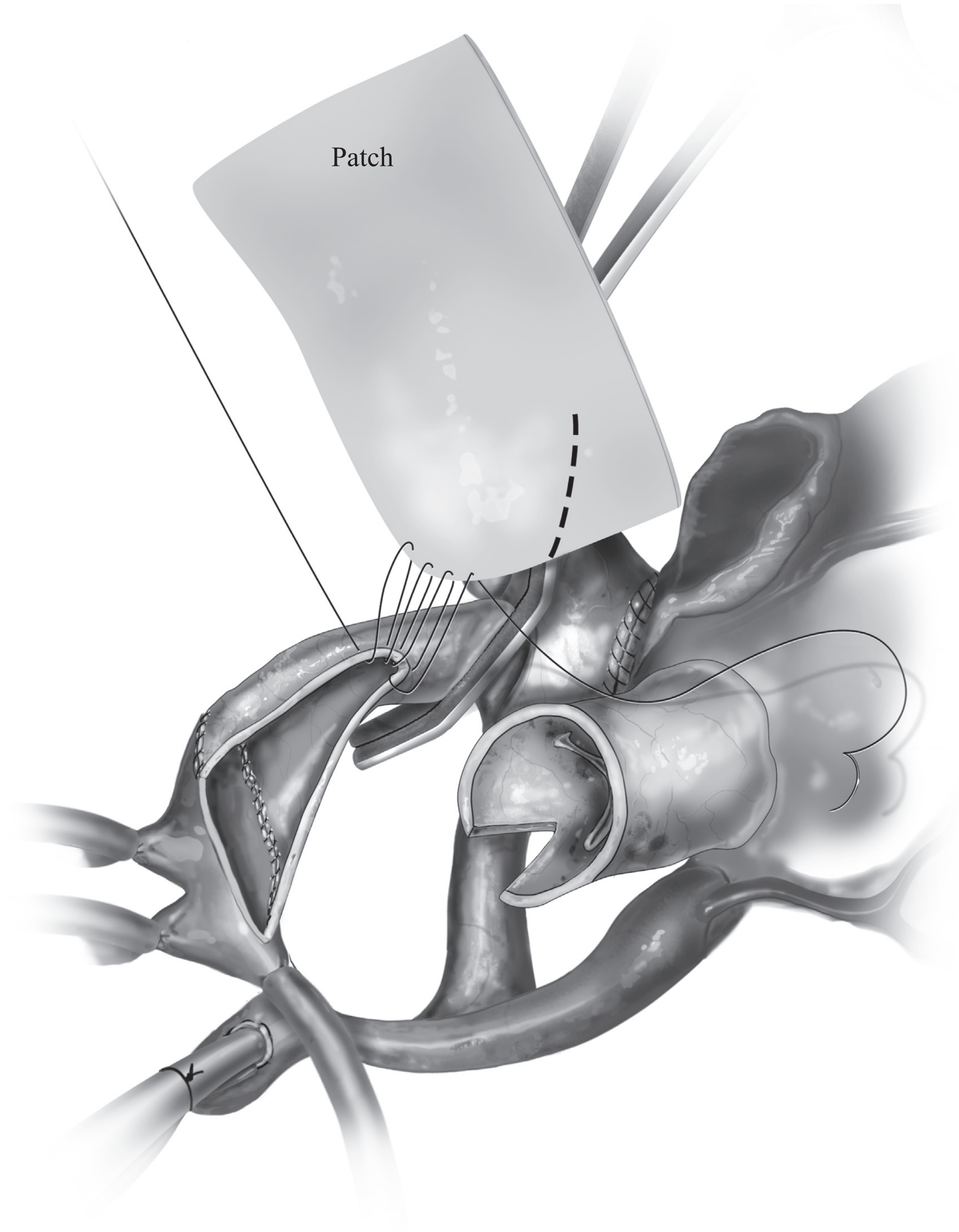

Figure 7 The distal transverse arch is sutured into the incision in the descending aorta. This suture line is continued almost to the snare on the transverse arch. A second longitudinal incision is made on the anterior aspect of the descending aorta and continued as far distally as possible. One corner is rounded off the rectangular patch, and a suture line is begun in the apex on the descending aorta and is sutured as far forward along the transverse arch as possible.

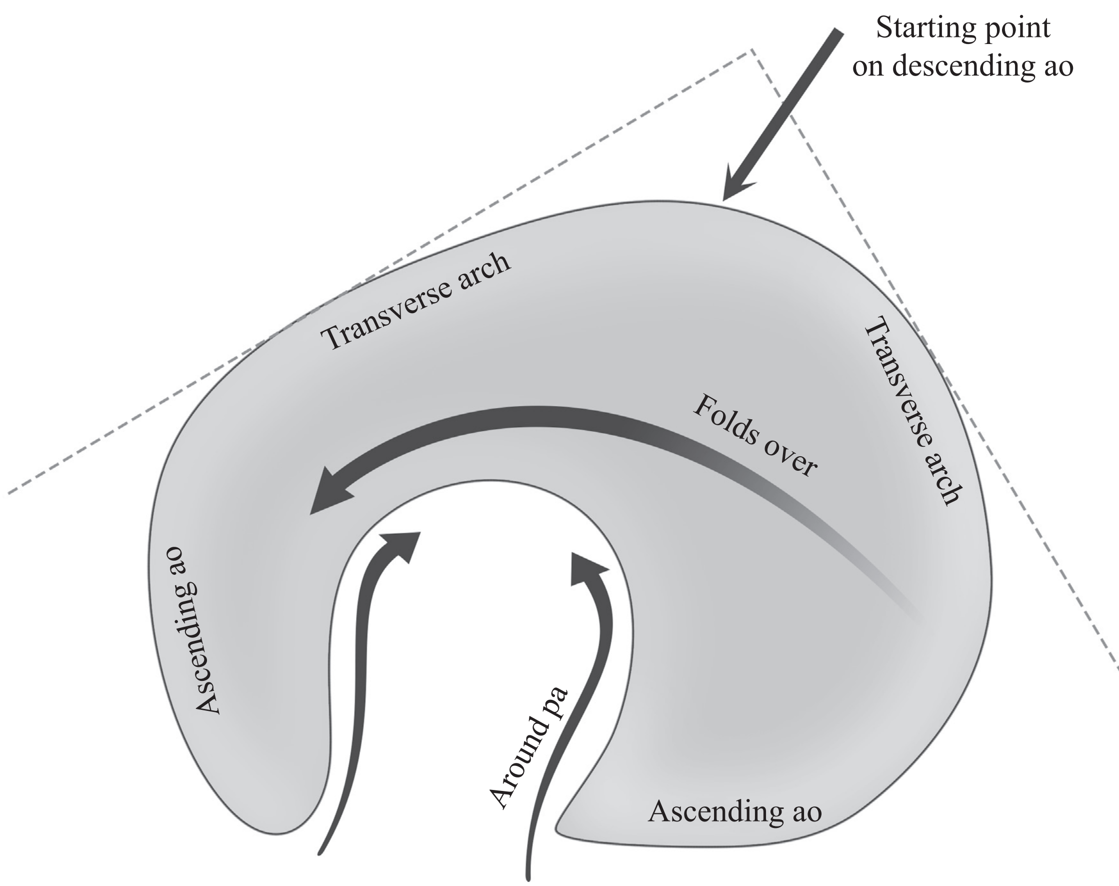

Figure 8 Homograft patch has been assiduously avoided for several years at the author's institution, owing primarily to concern about stimulation of alloimmunization, given that these patients occasionally are candidates for transplantation. Knitted Dacron patch can be used and has the advantage of being able to be shaped somewhat, but Dacron takes much longer to establish hemostasis after protamine administration. Currently the author uses an acellular xenograft matrix material patch (Cormatrix). This material gives excellent hemostasis and strength. The lack of elasticity and compliance of either material relative to homograft requires a different approach to the shape of the patch for creating the complex neoaortic reconstruction of the Norwood operation. That shape is demonstrated here.

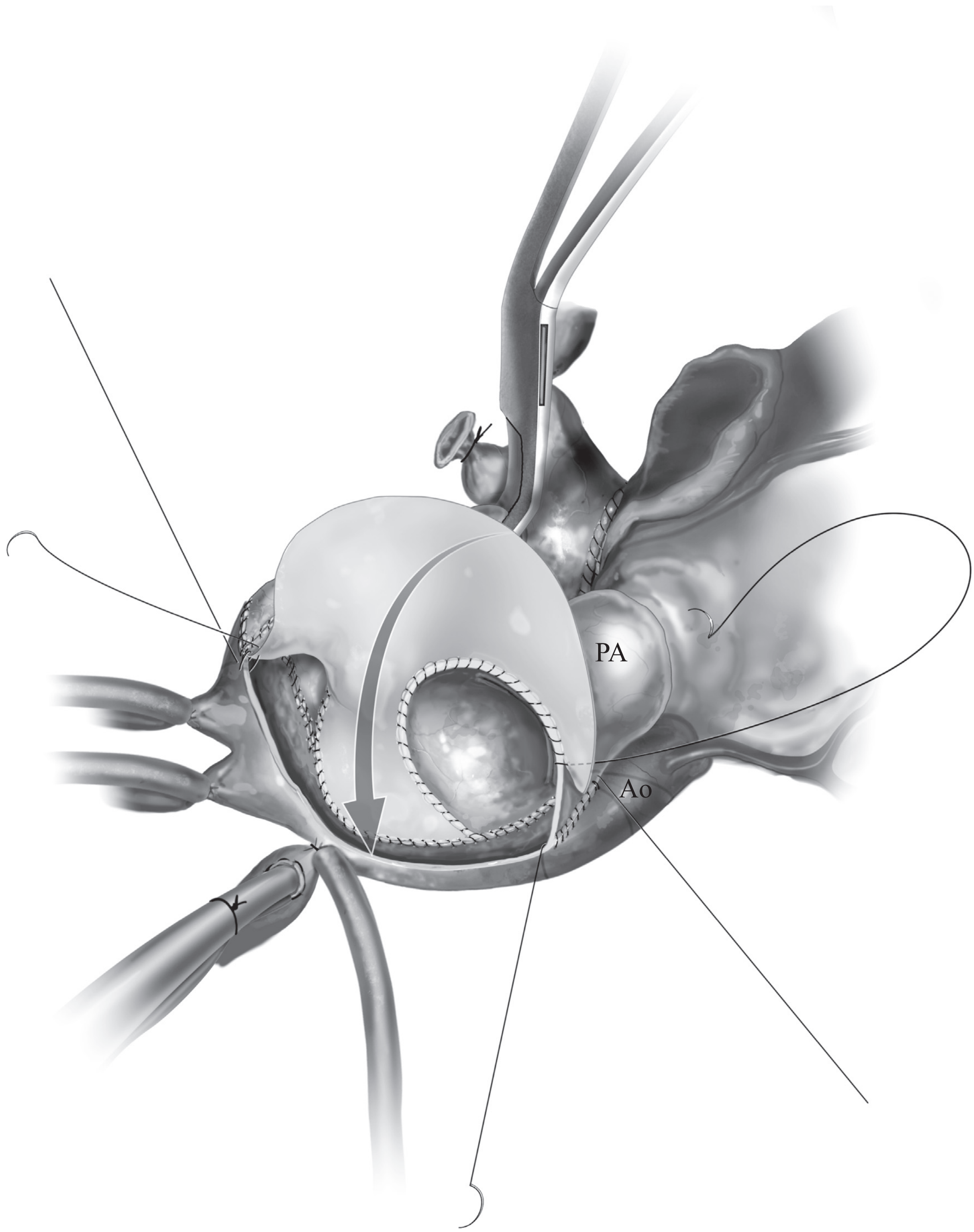

Figure 9 When the patch can be sutured no farther forward on the transverse arch, cardioplegic arrest is induced. The snare is tightened at the origin of the innominate artery, the transverse arch snare is opened, and a 2-mm olive tip cannula (Medtronic DLP arteriotomy cannula, 31002) is inserted into the ascending aorta and held with a snare for the delivery of antegrade cardioplegia. A larger aorta will take a 4-mm balloon-tipped cannula (Vitalcor). At the author's institution, Dr Del Nido's cardioplegic solution is delivered and not redosed for at least 1 hour. St. Thomas' solution could be redosed at the desired interval by holding the 4-mm balloon-tipped cannula in the opened aortic root. The longitudinal incision in the aorta is continued along the inner curvature and down the ascending aorta, directly opposite the pulmonary root. The aortic and pulmonary roots are separated. The incision in the aorta should extend to below the small sinotubular junction. A corresponding incision is made in the pulmonary root, usually just posterior to the nearest commissure of the pulmonary valve. This incision is made deeply enough so that the pulmonary root can be pulled somewhat toward the arch. The pulmonary root and aortic incisions are sutured side to side with a running suture. The posterior edge patch suture line is continued along the transverse arch. The patch is cut to make the posterior part lie flat, and the suture line is continued up to the "posterior corner" with the pulmonary root. The patch is cut back toward the descending aorta to create an oval opening into which the pulmonary root will be sutured. When using a noncompliant patch material, the final shape of the patch is as depicted in Figure 8. The patch suture line continues around the pulmonary root, and along the front edge of the arch and ascending incisions. The completed reconstruction is deaired before closing the suture line, then the snares and clamp are all removed, restoring perfusion to the heart.

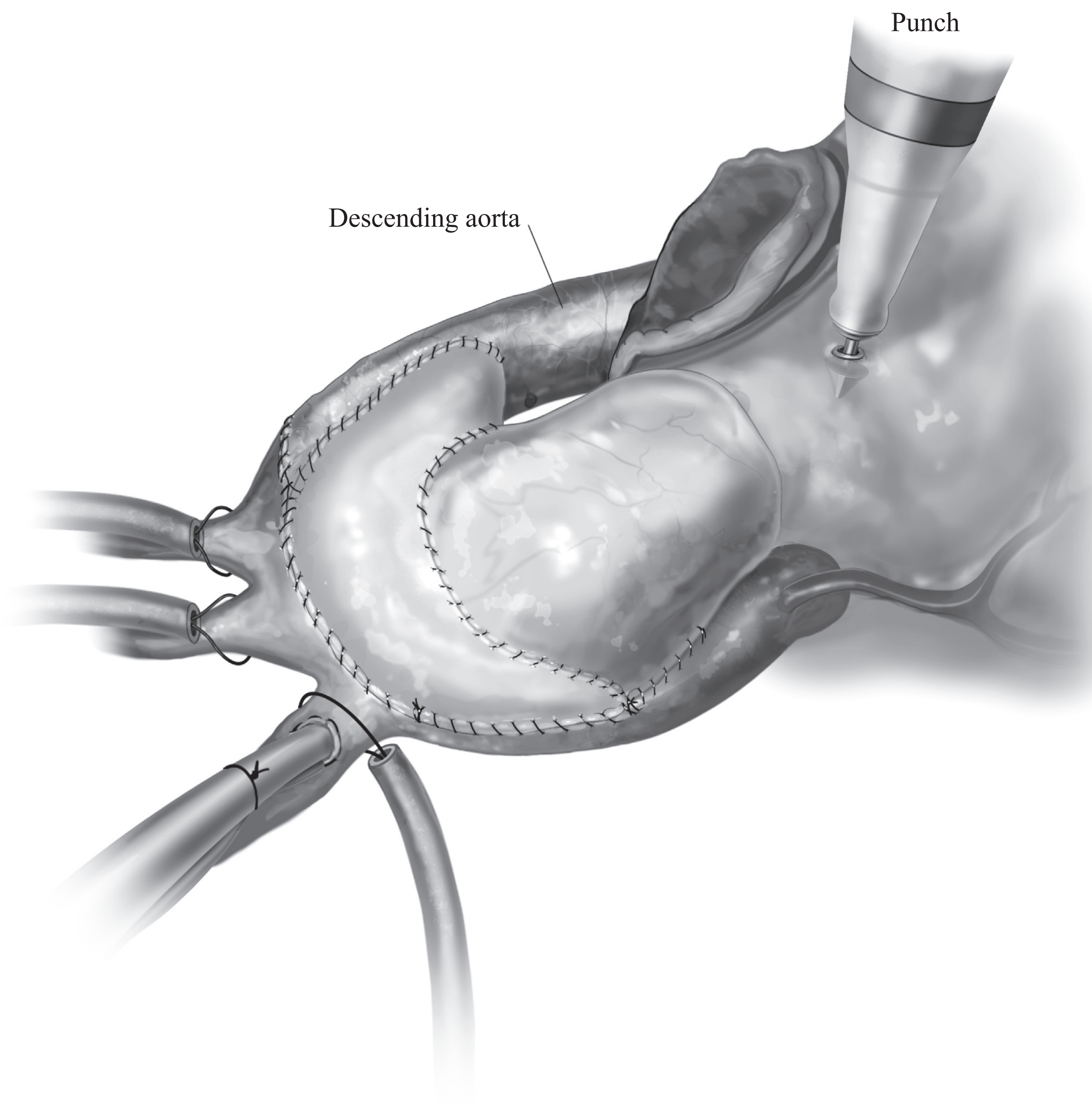

Figure 10 The ventriculotomy is widened using an aortic punch (Scanlon) until it stands open without retraction. The proximal end of the Sano is bevelled after carefully planning the length and sutured to the ventriculotomy. The beating ventricle is allowed to deair as this suture line is completed. The patient is now gradually separated from cardiopulmonary bypass. When flow has been reduced adequately so that the resistance of 1 arterial cannula is acceptable, the heart is elevated and the descending cannula is removed. Hemostasis of the descending cannulation site is carefully checked, then the heart is returned to anatomical position, and the site need not be checked again. After separation from bypass, modified ultrafiltration may be carried out. If return from the innominate artery cannula is problematic, it has occasionally been necessary to move this arterial cannula to a new purse-string site on the right atrium. The remainder of decannulation and closure are routine.

Postoperative Care Discussion

The innominate artery and descending aorta cannulation and continuous mildly hypothermic bypass technique is applicable to all neonatal aortic arch reconstruction and has become the exclusive technique at the author's institution. In the author's recent 5-year experience of the Norwood operation since the full implementation of this technique, survival to discharge has been 29/30 (97%). Delayed sternal closure was used in 4 patients (13%). Median duration of cardiopulmonary bypass was 116 minutes, and median myocardial ischemic time was 38 minutes, whereas for the 19 patients not having additional intracardiac procedures under cross clamp, these median times were 102 minutes and 22 minutes, respectively. Median duration of postoperative mechanical ventilation after intensive care unit arrival was 52 hours. In total, 10 patients were extubated within the first postoperative day, including 5 extubated in the operating room. Of these 5 patients, 2 required reintubation at some point before hospital discharge. Median duration of intensive care unit stay of those extubated within the first day was not different from those extubated 1-2 days after surgery or from the group as a whole (11 days).

An occasional complication that occurred during our earliest experiences with descending cannulation was pulmonary hemorrhage, which resulted in acute pulmonary dysfunction that in 2 cases required extracorporeal membrane oxygenation and was eventually fatal. We subsequently adopted the practice, described previously, of snare occluding the left pulmonary artery before any dissection in the left pulmonary hilum, and particularly, before the descending aortic exposure. Recently, with meticulous avoidance of retraction trauma to the lung and with left pulmonary artery snare occlusion, pulmonary hemorrhage has ceased to be a problem. Serious complications that might be feared owing to the descending cannulation, such as esophageal injury or aortic dissection, have not occurred.

There are considerable practical advantages to the dual cannulation technique. Because full perfusion flow is delivered to both the upper and lower body, there is no time constraint on the aortic reconstruction. An arch reconstruction that is not felt to be perfect can be revised immediately, without concern for accumulating duration of ischemia to the lower body. This lack of time limitation may also facilitate Norwood procedure learning by the trainee or might allow adoption of a more time-consuming arch technique such as coarctectomy with interdigitating reanastomosis.[6]

The avoidance of deep hypothermia results in improved preservation of hemostatic function and decreased blood product administration.[7] Improved preservation of renal function, which we reported in 2013, results in better postoperative urine production and decreased third-space fluid gain.[8] Postoperative function of the other abdominal organs remains to be investigated.

Although the described technique seems to be associated with important reductions in postoperative morbidity, its development has occurred concurrently with other improvements in perioperative care. Prospective study is ongoing. The overall pace of convalescence after Norwood procedure may be as much controlled by the persistence of single ventricle physiology as it is by postsurgical issues: the value of immediate postoperative extubation in altering the time course of hospitalization is not yet at all clear. However, as duration of mechanical ventilation and duration of intensive care unit stay are among factors that predict eventual neurodevelopmental outcome, this and other technical modifications that have the potential to reduce the morbidity of the Norwood operation warrant further investigation.

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